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COMPACT X-RAY AND BREMSSTRAHLUNG COLLIMATOR FOR LCLS-II

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Abstract

Beam collimation is crucial to maintaining machine and personal safety during LCLS-II operation. This paper discusses a compact collimator consisting of an X-ray beam power collimator, a burn through monitor (BTM) designed to detect failure of the X-ray beam collimator, and a Bremsstrahlung collimator. The x-ray collimator body is a monolith machined from CuCrZr that eliminates costly braze operations and reduces assembly time and complexity. Sintered high thermal conductivity SiC is employed as the X-ray absorber. The allowed beam power is limited to 100W and 50W/mm^2. Finite element analyses (FEA) ensure that the power absorber remains in safe temperature and stress regimes under the maximum power loading and smallest expected beam dimensions. Beam containment requirements stipulate the inclusion of a monitor to detect burn through events owing to absorber failure. The BTM is a gas-filled, thin wall vessel which, if illuminated by the beam, will burn through and release the contained gas and trip pressure switches that initiate beam shutdown. The beam absorber and BTM shadow the Bremsstrahlung collimator shielding after appropriate propagation of manufacturing, assembly, and installation tolerances. Tooling is developed to minimize assembly complexity and ensure minimal alignment errors.

INTRODUCTION

This presentation discusses a package consisting of photon collimator that intercepts and collimates the x-ray beam, Burn Through Monitor (BTM) that monitor for beam excursion from the design path, and Bremsstrahlung collimator which collimates high energy photons associated with electron beam interaction with residual gas and physical aperture. In general those three components are situated in sequence along a given beam line though in some cases not all three elements are required.

The key requirement for this design were:

- Design a compact and modular x-ray power and Bremsstrahlung collimators.
- X-ray collimator to handle allowed power of 100W.
- Come up with fixtures and locating features to minimize the relative alignment error on assembly and hence maximize allowed beam aperture while providing downstream beam containment.

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DESIGN

X-ray Collimator

Previously designed collimator bodies have employed a vacuum nipple with welded flanges and braised copper elements that provide cooling for the beam intercepting disk. For this design the body is a monolithic machined Copper alloy CuCrZr (18150) that allows compact design with integrated conflat seal knife edges and eliminates the need for flanges welding [1]. See Fig. 1. In addition, the cooling channels are machined in the body which eliminates the brazing of an additional cooling block. The resulting mask body extends 72mm along the beam direction.

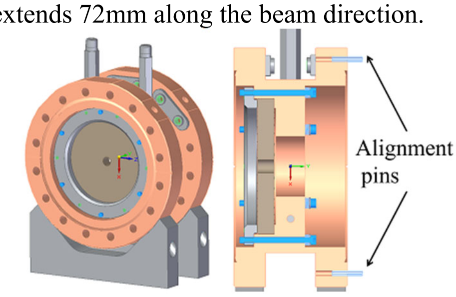

Figure 1: X-ray collimator. (a) CAD model, (b) cross section.

X-ray collimators are illuminated by x-ray beam power composed of high intensity, high frequency, short duration pulses. The collimator must not be damaged by the average beam power nor ablated through pulse by pulse energy deposition. Sintered high thermal conductivity SiC is employed as the x-ray absorber with design provisions incorporated to permit the inclusion of additional absorbers (e.g. diamond). The allowed beam power is limited to 100W.

The first beam intercepting element is cooled indirectly via indium mediated conduction cooling by the water-cooled collimator body. Figure 2 shows that the indium is positioned in the shadow of the beam intercepting element and maintained safely under the indium melting temperature at maximum power loading and maximum beam missteering.

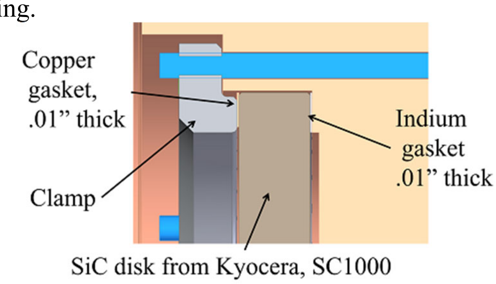

Figure 2: Design interface around SiC disk.

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The CuCrZr body is designed for reduced water consumption of 1.25 GPM relative to the LCLS-II photon collimator design. That flow is consistent with 15 ft/sec flow in a 0.186in ID tube (0.25in OD tube).

Finite Element Analysis of SiC

FEA are performed to ensure the components that intercept the free electron laser (FEL) beam shall remain in safe temperature and stress regimes under the maximum power loading and smallest expected beam dimensions. ANSYS workbench is used to perform the analysis. First, the thermal analysis is run to obtain the temperature field of the SiC disk. Second, the temperature profile is used as a thermal load in a structural analysis to determine the stresses in the disk. Figure 3 shows the three components that were analyzed and Table 1 provides the material properties. Bolt holes and small features were removed from the collimator housing with the goal of reducing analysis run time and mesh simplification. See [2] for Indium mechanical properties.

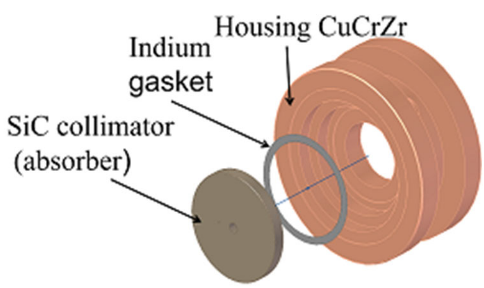

Figure 3: Exploded view of simplified geometry for FEA.

Table 1: Material Properties

Property	CuCrZr	SiC
Density, [g/mm^3]	8.91	3.16
Thermal Conductivity, [W/m-K]	323	f(temp)*
Coeff of Thermal Expansion, [10^{-6}x1/K]	18.6	3.9
Young's Modulus,[GPa]	128	430
Poisson Ratio	0.18	0.17

*f(temp) is given as: at room temperature, the thermal conductivity is 200W/m-K and at 600°C it is 82 W/m-K.

Thermal Conductance is applied at the interface between the SiC disk and Indium gasket. Indium foil interface conductance is modeled at 0.010W/mm^2-K per A.M. Khounsary *et al.* [3].

The results of two cases, properly steered and significantly mis-steered beam, are shown in Table 2 and Table 3, respectively.

Table 2: Properly Steered 2.1mm Beam Diameter

Power	100W	50W
Max Temp, °C	845	323
Max Principal Stress, [MPa]	87	24
Min principal Stress, [MPa]	751	216

Table 3: Significantly Mis-Steered 2.1mm Beam Diameter

Power	100W	50W
Max Temp, °C	715	284
Max Principal Stress, [MPa]	26	10
Min principal Stress, [MPa]	675	208

The temperatures shown in Tables 2 and 3 are higly localized to the beam location. The peak temperatures at the indium interface are below the melting point of indium for all cases.

Flexural Strength of SiC from Kyocera (SC1000) is 480 MPa. Very conservatively, the tensile strength is 1/3 of the flexural strength. In this case the tensile strength will be 160 MPa. Results show maximum principal stress always below that level. Compressive strength of SiC varies between 3860 MPa and 4800 MPa. Results show minimum principal stress well below those values.

Burn Through Monitor

The BTM is a gas-filled, thin wall vessel which if illuminated by FEL beam will burn through thus releasing the contained gas (Fig. 4). Redundant gas channels communicate with the gas-filled vessel. The pressure in these gas channels is monitored by pressure switches which safely terminate the beam if rapid reduction of gas pressure indicates a burn through event. The BTM gas-filled cavity must shadow the Bremsstrahlung collimator shielding after appropriate propagation of manufacturing, assembly, and installation tolerances. Stresses in the edge weld are calculated using Roark, table 24, case 10b.

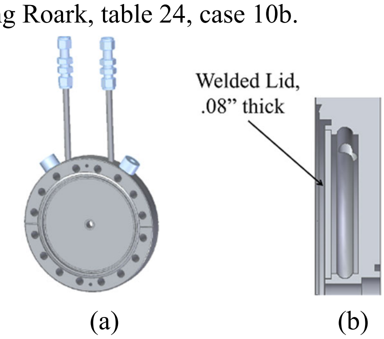

Figure 4: BTM, (a) CAD model, (b) cross section.

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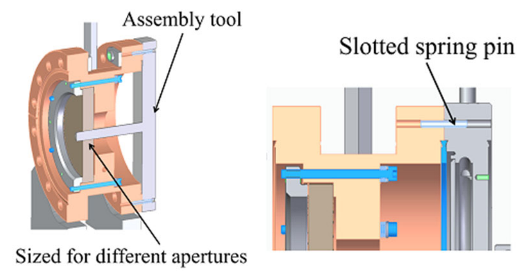
Bremsstrahlung Collimator

The Bremsstrahlung radiation is handled by a vacuum nipple and a block of tungsten alloy. The longitudinal length that intercepts the beam is ≥80mm and the beam aperture is completely shadowed by the x-ray collimator and BTM.

ASSEMBLY AND ALIGNMENT

The photon collimator aperture in conjunction with manufacturing, assembly, and installation tolerances define the cone transmitted to downstream components. The BTM and Bremsstrahlung collimator including the associated vacuum walls are not illuminated by the beam. Rather these components shall be safely shadowed by the photon collimator.

Holes for alignment pins have been incorporated in the flange of each component ensuring common reference and well defined flange position. Figure 5a shows alignment tool for different aperture sizes. The tool uses the pins as a reference and positions the SiC aperture. On Fig. 5b one can see how the BTM is mounted onto the collimator flange using the alignment pins and hence transferring relative alignment of SiC aperture to BTM and Bremsstrahlung collimator.



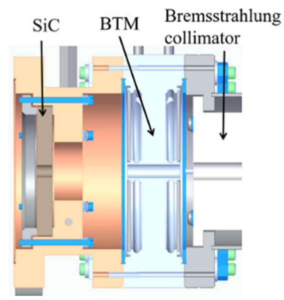
(a) (b)

Figure 5: Assembly process. (a) Cross section of SiC disk installation, (b) cross section of collimator and BTM.

A list below shows an example of the diameter of the clear line of sight (CLS) for each component. Those values are calculated after taking into consideration the pin position tolerance, tooling tolerances and apertures dimensional tolerances and making sure each component shadows the next one downstream:

- SiC aperture: min CLS 7.48mm, max CLS 8.26mm.
- BTM aperture: min CLS 8.26mm, max CLS 9.1mm.
- BTM gas volume: min CLS 10.05mm, max CLS 11.14mm.
- Bremsstrahlung collimator aperture: min CLS 11.14, max CLS 12.03mm.

Figure 6 shows the clear line of sight for the whole assembly and Fig. 7 is a photograph of the final installed support structure and three components.



(a) (b)

Figure 6: Cross section of a whole assembly.

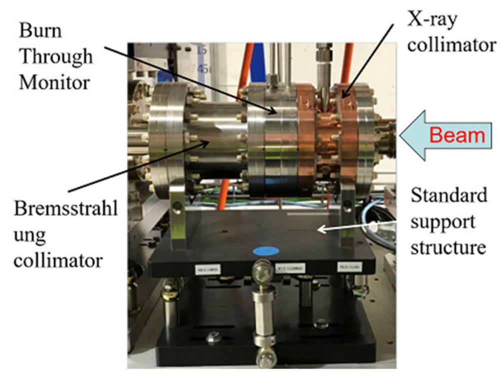


Figure 7: Final installed support structure with three components.

CONCLUSION

The design package is a compact, modular x-ray power and Bremsstrahlung collimator for beam containment. The FEA analysis of properly steered and significantly miss-steered beam confirmed the x-ray collimator (SiC) can handle up to 100W and 50W/mm^2.

The assembly tools and alignment pins ensure high relative alignment tolerance. Allowed beam is maximized and good downstream beam containment is provided.

Many packages with different sizes SiC disks, BTMs, and Bremsstrahlung collimators were installed in early 2019 and are operating successfully under the designed conditions.

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